

Four-Lepton Resonance at the Large Hadron Collider

Vernon Barger¹ and Hye-Sung Lee²

¹*Department of Physics, University of Wisconsin, Madison, WI 53706, USA*

²*Department of Physics, Brookhaven National Laboratory, Upton, NY 11973, USA*

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A spin-1 weakly interacting vector boson, Z' , is predicted by many new physics theories. Searches at colliders for such a Z' resonance typically focus on lepton-antilepton or top-antitop events. Here we present a novel channel with a Z' resonance that decays to 4 leptons, but not to 2 leptons, and discuss its possible discovery at the Large Hadron Collider. This baryonic gauge boson is well motivated in a supersymmetry framework.

I. INTRODUCTION

Many models of physics beyond the Standard Model (SM) have an extra Abelian gauge group $U(1)$ [1]. There are many options for this $U(1)$ gauge symmetry and the corresponding Z' from the broken symmetry can enable its identification. The Drell-Yan process, wherein the Z' is produced from quark-antiquark fusion and decays to a lepton-antilepton pair, can give a particularly clear signal at a hadron collider [2, 3].

However, the lepton pair search for a Z' is nullified if the Z' does not couple to the SM leptons. Searches can still be made for dijet decay products of a Z' , but the QCD dijet backgrounds are huge and fog such a signal [4, 5]; hence, a Z' resonance may not be discovered in dijets [6, 7], especially if its coupling strength to quarks is not large, although a signal in the top pair channel could be easier to recognize [8, 9].

Our interest here is in a 4-lepton signal from a leptophobic Z' that can be produced at the LHC (and the Tevatron) with a large cross section and give a 4-lepton signal comparable to that of the lepton pair signals of generic Z' models. Specifically, we consider a Z' resonance in which the 4-leptons final state is bridged by pair production of a new scalar boson (φ). The Z' couples to quark pairs and φ , but not to lepton pairs, and the new scalar φ decays into a lepton pair (see Fig. 1). LHC experiments, and possibly Tevatron experiments, can find or reject this distinctive 4-lepton signal.

A leptophobic Z' may also appear as a resonance in a 6-lepton final state; a future search for this signal at the LHC requires $\sim 100 \text{ fb}^{-1}$ integrated luminosity at 14 TeV center-of-mass (CM) energy [10].

II. MODEL

We begin by introducing a specific model in which a 4-lepton Z' resonance can be realized without having a corresponding lepton pair signal. We consider a generic supersymmetry (SUSY) framework where scalar fields are abundant. The baryon number (B) is not preserved in the SUSY framework and in general the proton is unstable. Thus a gauged B has been sought, but then additional fermions are required to cancel the anomaly

[11–17]. One natural way of anomaly cancellation is to add a fourth-generation (4G) of fermions. Then, by requiring all quarks carry $B(=1/3)$, the 4G lepton charge is uniquely determined to be -4 by the anomaly free condition:

$$\begin{array}{ll} \text{SM quarks: } 1/3, & \text{SM leptons: } 0, \\ \text{4G quarks: } 1/3, & \text{4G leptons: } -4. \end{array}$$

This is effectively $U(1)_B$ for the SM fermions: every SM quark has B as a charge, and every SM lepton has 0 charge¹.

Although proton stability would not have been guaranteed once the $U(1)_B$ is broken spontaneously, it turned out there exists a residual \mathbb{Z}_4 discrete symmetry, called baryon tetrality (\mathbb{B}_4), that forbids proton decay [19]. Under \mathbb{B}_4 , lepton number violating operators can exist (such as $\lambda L L E^c$ and $\lambda' L Q D^c$), but not baryon number violating operators (such as $\lambda'' U^c D^c D^c$).

In order to have the \mathbb{B}_4 residual discrete symmetry, the Higgs boson that spontaneously breaks the $U(1)_B$ gauge symmetry (typically, a new Higgs singlet) should have a $U(1)_B$ charge of 4 or -4 [19]. Since it coincides with the $U(1)_B$ charge of the N_4^c [4G right-handed neutrino and sneutrino (superpartner of neutrino)], we can adopt the approach of Ref. [20] in which the 4G right-handed sneutrino (let us call it S) with a vacuum expectation value (vev) is used to break the $U(1)_B$ without the

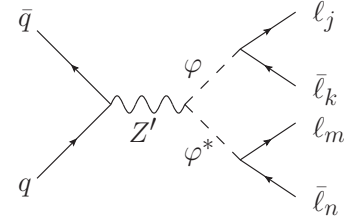


FIG. 1: 4-lepton Z' resonance diagram at a hadron collider.

¹ It was pointed out that the a baryonic Z' can be a possible source of the Wjj anomaly recently reported in the Tevatron CDF experiment [18].

need for a separate singlet. In general, the 4G sneutrino (left-handed one) can also have a vev through a mixing although we will assume the mixing is very small.

Because the 4G Majorana neutrino mass term is forbidden by the $U(1)_B$ symmetry, the 4G neutrino is a Dirac particle on which the seesaw mechanism does not work, and thus can easily satisfy the LEP Z width measurement that is compatible only with 3 light active neutrinos [21].

We take the 4G sneutrino ($\tilde{\nu}_4$), the spin-0 companion of the 4G neutrino, as a bridging scalar between the Z' and the lepton final states. It has a nonzero $U(1)_B$ charge (-4) and can couple to the Z' while the sneutrinos of the first 3 generations have vanishing $U(1)_B$ charge. We assume the $\tilde{\nu}_4$ is the Lightest Superpartner (LSP); it can decay into a lepton pair through the lepton number violating interaction $\lambda_{ijk} L_i L_j E_k^c$. (For instance, see Ref. [22].) A nonzero $U(1)_B$ charge for the 3-generation sneutrinos would inevitably have led to 2-lepton Z' resonance [23].

In the remainder of this paper, we focus on the collider physics consequences of this scenario with the $\tilde{\nu}_4$ LSP. Our analysis does not necessitate this particular supersymmetric model, albeit well motivated. Rather, the model serves as an existence proof of a consistent theory of the 4-lepton Z' resonance without a 2-lepton Z' resonance, and also provides a specific realization of the phenomenology of a new scalar that couples to the Z' and lepton pairs.

III. LEPTONIC DECAY OF THE NEW SCALAR PARTICLE

Here, we discuss some characteristic features of the $\tilde{\nu}_4$ LSP decay exclusively through lepton number violating operators. Renormalizable operators $\lambda_{4jk} L_4 L_j E_k^c$ and $\lambda'_{4jk} L_4 Q_j D_k^c$ are forbidden by the $U(1)_B$ gauge symmetry. Although operators with two 4G fields such as $\lambda_{4j4} L_4 L_j E_4^c$ and $\lambda'_{4j4} L_4 Q_j D_4^c$ (or $\lambda'_{44k} L_4 Q_4 D_k^c$) are allowed at the renormalizable level, $\tilde{\nu}_4$ decays cannot be mediated by these operators due to kinematics when $\tilde{\nu}_4$ is the lightest of the 4G states. Thus, nonrenormalizable operators $\lambda_{4jk} \frac{\langle S \rangle}{M} L_4 L_j E_k^c$ and $\lambda'_{4jk} \frac{\langle S \rangle}{M} L_4 Q_j D_k^c$ with a heavy mass parameter M allow $\tilde{\nu}_4$ decays since $z[S] = 4$. Taking λ_{4jk} , $\lambda'_{4jk} \approx 1$ and $M/\langle S \rangle = 10 - 1000$, for instance, effective coefficients $\lambda_{4jk}^{\text{eff}} \equiv \lambda_{4jk} \frac{\langle S \rangle}{M}$, $\lambda'_{4jk}^{\text{eff}} \equiv \lambda'_{4jk} \frac{\langle S \rangle}{M} \approx 0.001 - 0.1$ are obtained².

Neglecting the light fermion masses, we obtain the par-

tial widths

$$\Gamma(\tilde{\nu}_4 \rightarrow \ell_j^+ \ell_k^-) = \frac{1}{16\pi} (\lambda_{4jk}^{\text{eff}})^2 m_{\tilde{\nu}_4}, \quad (1)$$

$$\Gamma(\tilde{\nu}_4 \rightarrow \bar{d}_j d_k) = \frac{3}{16\pi} (\lambda'_{4jk}^{\text{eff}})^2 m_{\tilde{\nu}_4}. \quad (2)$$

If we take all $\lambda' = 0$, the $\tilde{\nu}_4$ LSP would decay only through $\lambda_{4bc}^{\text{eff}}$ ($b, c = 1 - 3$) with a total decay width given by

$$\Gamma_{\tilde{\nu}_4} = \frac{m_{\tilde{\nu}_4}}{16\pi} [(\lambda_{411}^{\text{eff}})^2 + (\lambda_{412}^{\text{eff}})^2 + (\lambda_{413}^{\text{eff}})^2 + (\lambda_{421}^{\text{eff}})^2 + (\lambda_{422}^{\text{eff}})^2 + (\lambda_{423}^{\text{eff}})^2 + (\lambda_{431}^{\text{eff}})^2 + (\lambda_{432}^{\text{eff}})^2 + (\lambda_{433}^{\text{eff}})^2]. \quad (3)$$

It is demanded that $m_{\tilde{\nu}_4} \gtrsim M_Z/2$ by the result of the LEP Z decay experiment. The $\lambda_{4jk}^{\text{eff}}$ can be constrained by various experiments such as $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$ and similar τ decays. The bounds depend on the final lepton flavor indices (j, k), and currently the most severe bound comes from $\text{Br}(\mu \rightarrow eee) < 1.0 \times 10^{-12}$, which translates into $|\lambda_{i12}^* \lambda_{i11}| < (6.6 \times 10^{-7}) \times (m_{\tilde{\nu}_i}/100 \text{ GeV})^2$ for $\tilde{\nu}_i$. In a flavor-blind sense, it corresponds to $|\lambda_{4jk}^{\text{eff}}| < 0.0008 \times (m_{\tilde{\nu}_4}/100 \text{ GeV})$ for the $\tilde{\nu}_4$ LSP with the other $\tilde{\nu}$'s sufficiently heavy [24]. That is $|\lambda_{4jk}^{\text{eff}}| < 0.0004$ (0.0016) for $m_{\tilde{\nu}_4} = 50 \text{ GeV}$ (200 GeV), which falls into the ballpark of the aforementioned $\lambda_{4jk}^{\text{eff}}$ value for $M/\langle S \rangle = 1000$. Larger $\lambda_{4jk}^{\text{eff}}$ may be allowed for a specific choice of (j, k) as the experimental bounds are flavor-dependent. Because of many free parameters in $\Gamma_{\tilde{\nu}_4}$, a wide range of $\text{Br}(\tilde{\nu}_4 \rightarrow \ell_j^+ \ell_k^-)$ for a given $\ell_j^+ \ell_k^-$ can be accommodated.

IV. COLLIDER PHENOMENOLOGY

In this section we present quantitative cross section predictions of the 4-leptons channel for the LHC7 (LHC with 7 TeV CM energy) experiments. For the calculations we use **Comphep/Calcchep** [25, 26], with some modifications, and the parton distribution function of **CTEQ6L** [27, 28].

For definiteness, we take the Z' gauge coupling constant to be $g_{Z'} = 0.1$; the Z' production cross section and Z' width can be simply scaled by $(g_{Z'}/0.1)^2$ for other $g_{Z'}$ values. We assume that the $\tilde{\nu}_4$ LSP is the lightest 4G field, with $m_{\tilde{\nu}_4} = 50 \text{ GeV}$, and that all new particles, except for the $\tilde{\nu}_4$ LSP, have masses larger than $M_{Z'}/2$ so that Z' decays only into the SM fermions and the $\tilde{\nu}_4$ pair. Thus, the total Z' width we take is the minimum value, which is $\Gamma_{Z'} \approx 1.6 \times 10^{-3} M_{Z'}$ for $M_{Z'} \gg m_{\tilde{\nu}_4}$.

The 4-lepton Z' resonance cross section is

$$\sigma(pp \rightarrow 4\ell) \simeq \sigma(pp \rightarrow Z') \text{Br}(Z' \rightarrow \tilde{\nu}_4 \tilde{\nu}_4^*) \text{Br}(\tilde{\nu}_4 \rightarrow 2\ell)^2. \quad (4)$$

The branching fraction is $\text{Br}(Z' \rightarrow \tilde{\nu}_4 \tilde{\nu}_4^*) \simeq 0.67$ for $M_{Z'} \gg m_{\tilde{\nu}_4}$. The $\tilde{\nu}_4$ branching fractions to the light leptons ($ee, e\mu, \mu\mu$) are parameter dependent and flavor nonuniversality is expected. We shall illustrate the case $\text{Br}(\tilde{\nu}_4 \rightarrow 2\ell) = 1$, which is indeed possible to arrange.

² $\langle S \rangle \lesssim 1 \text{ TeV}$ is expected in SUSY to keep the extra D -term contribution to the sfermion masses small, and $M = 10 - 1000 \text{ TeV}$ satisfies bounds on the scale of new physics from various constraints such as neutral kaon mixing.

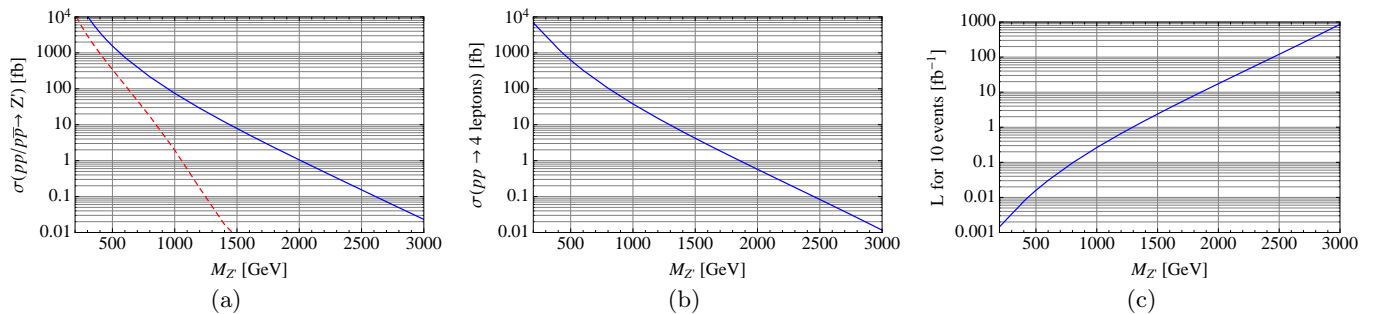


FIG. 2: (a) Z' production cross section at the LHC7 ($E_{\text{CM}} = 7$ TeV) (solid curve) and the Tevatron ($E_{\text{CM}} = 1.96$ TeV) (dashed curve). (b) Cross section of 4-leptons after cuts at the LHC7. (c) Luminosity for 10 events after cuts at the LHC7.

Figure 2 (a) shows the Z' production cross section at the LHC (solid curve) and Tevatron (dashed curve), for the Z' mass range $M_{Z'} = 200 - 3000$ GeV. The low mass region would have been excluded by the dilepton Z' resonance searches at the LHC had a Z' coupled to the light leptons. For instance, the current bound on the sequential Z' model is already $M_{Z'} \gtrsim 1.8 - 1.9$ TeV [2, 3] though its couplings are larger than our benchmark coupling. The ratio of the Tevatron to LHC Z' production cross sections is about 0.2 for $M_{Z'} = 500$ GeV, and it drops rapidly at higher $M_{Z'}$. Though it might be possible to have an observable 4-lepton resonance at the Tevatron, especially for the low Z' mass region, we will focus on the LHC experiments in our analysis.

Figure 2 (b) shows the 4-lepton Z' resonance cross section at the LHC after the following typical acceptance cuts and Z' invariant mass cut:

- (i) $p_T > 15$ GeV (each lepton),
- (ii) $|\eta| < 2.5$ (each lepton),
- (iii) $|m_{\text{inv}}(4\ell) - M_{Z'}| < 3\Gamma_{Z'}$ (4-leptons).

The SM 4-lepton background to ee and $\mu\mu$ pairs is principally from the $q\bar{q} \rightarrow ZZ$ subprocess. As a recent ATLAS analysis shows, with nearly the same p_T and η cuts as ours, the SM background is negligible when the $m_{\tilde{\nu}_4}$ mass is outside the Z window of $(66 - 116)$ GeV [29]. Furthermore, some 4-lepton combinations (such as $ee\mu\mu$, $e\mu\mu\mu$) do not have any significant SM backgrounds. Thus, through all the Z' mass range, we will require a small number of 4-lepton events (10 events) after the acceptance cuts, in order to estimate the discovery reach.

Figure 2 (c) shows the required luminosity at LHC7 to realize a signal of 10 events at a 4-lepton resonance as read from Fig. 2 (b). For $g_{Z'} = 0.1$, an integrated luminosity at LHC7 of $L \simeq 17 \text{ fb}^{-1}$ is needed for discovery (10 events) of $M_{Z'} = 2$ TeV. The existence of a 4-lepton Z' resonance is already being probed at LHC7 in terms of the $M_{Z'}$ and $g_{Z'}^3$ and an integrated luminosity of 5 fb^{-1}

in each detector is expected before the end of 2011. The current LHC dijet search results (with $L \sim 1 \text{ fb}^{-1}$) do not constrain the model for $g_{Z'} = 0.1 - 0.3$, as can be deduced from the estimates in Ref. [30].

A 4-lepton signal could be confused initially with a possible Higgs signal from $H \rightarrow ZZ$ with each Z decaying to lepton pairs. There are several distinguishing characteristics of the signals: (i) Z decay includes neutrino decay modes that are absent in $\tilde{\nu}_4$ decay; (ii) $\tilde{\nu}_4$ can decay into different lepton flavors which allows final states like $ee\mu\mu$ and $e\mu\mu\mu$, although these could be switched off by $\lambda_{412}^{\text{eff}} = \lambda_{421}^{\text{eff}} = 0$; (iii) The angular distribution of leptons in their rest frame is flat for the scalars (Higgs and sneutrino), but θ -dependent for the vectors (Z and Z'); (iv) If the $\tilde{\nu}_4$ mass differs from the Z boson mass, the lepton pair invariant mass distributions from the sneutrino decays would peak at a value different from M_Z , either lower or higher; and (v) $H \rightarrow ZZ$ should be accompanied by $H \rightarrow WW$, with a ratio of about 1 to 2.

Another exotic possibility for 4-lepton events is that a Higgs-like boson is produced via gluon-gluon fusion and it decays to a pair of hidden sector fields (vectors or scalars), each of which then decay to two leptons [31, 32]. The production cross section for a Higgs boson via gluon-gluon fusion would be much larger at LHC7 than at the Tevatron.

Though we have limited ourselves to only 4-lepton events, it is straightforward to extend the idea to other 4-fermion resonances depending on the values of λ^{eff} and λ'^{eff} , such as 4τ , $2\ell + 2b$, $4t$, etc.

V. SUMMARY

We have discussed a novel Z' search channel in which a 4-lepton Z' resonance can be produced at the LHC without an accompanying 2-lepton Z' resonance signal. We have shown that it is possible to construct a consistent supersymmetric model which has a Z' particle with this property. The $U(1)$ symmetry of the model respects the baryon number for the first three generations. The model is made anomaly free by the addition of a fourth gener-

³ A direct application of the ATLAS analysis $\sigma_{4\ell} < 4.7 \text{ fb}$ (with 3-events criteria and $L = 1.02 \text{ fb}^{-1}$) [29] gives $M_{Z'} \gtrsim 1500$ GeV for $g_{Z'} = 0.1$.

ation of fermions. Then the Z' can decay to the fourth generation sneutrino pair, which in turn decay into lepton pairs, thus giving the 4-lepton resonance signal. The Z' and the $\tilde{\nu}_4$ can be discovered or excluded in the near future by the LHC experiments.

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